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Abstract

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Disciplines

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Analysis of surface roughness alteration in micro flexible rolling

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Abstract

Thin strip with varying thickness, a novel structural and functional material, is fabricated by micro flexible rolling, and has three thickness features including the thicker zone, the thinner zone and the transition zone. Rolling and roll lifting speeds determine the thickness distributions, and have a great influence on the surface roughness, then the final product quality which is of significant importance for thin materials in subsequent processing. In this study, surface roughness alteration of aluminium alloy strips during micro flexible rolling was investigated with considering the influences of rolling speeds, roll lifting speeds, thickness ratios (the ratio of the thicker zone to the thinner zone) and lubrication conditions, and the mechanisms were discussed. The results show that rolling parameters have a significant effect on the alteration of surface roughness from the thicker zone to the thinner zone along the rolling direction. The experimental observations indicate that the surface roughness of thin strips with varying thicknesses presents a decreasing tendency with the increase of contact area results from downward rolling phase along the transition zone, however, it is constantly higher than that in the upward rolling phase.

Keywords: Micro flexible rolling; Surface roughness alteration; Rolling parameters; Upward and downward rolling phases; Lubrication

1 Introduction

Micro flexibly rolled product has wide applications in the area of micro electromechanical systems and micro system technologies [1-3]. Surface roughness of micro flexibly rolled strip (MFRS) becomes notably important since it not only affects the energy consumption during processing but also influences the surface finishing, dyeing quality, wear and fatigue properties, and dimensional tolerance of the final products [4-6]. In this context, understanding the manner how surface roughness evolves in micro flexible rolling is a crucial aspect needs to be comprehended.

The surface roughness has a close relationship to the lubrication regime during the rolling process. Regarding this, three major lubrication regimes, which includes the boundary, mixed and hydrodynamic lubrication regimes, have been commonly considered [7-10]. Among them, the 'mixed lubrication regime' is the most acceptable one for the rolling process, which refers to a combination of hydrodynamic regime dragging lubricant to the roll-workpiece interface and a portion of direction contact regime of the asperities from both rolls and the strip. For hydrodynamic lubrication regime, a large number of studies [11, 12] have been conducted based on the Reynolds's equation which describes the oil pressure development as the variation of oil film thickness. Following this, two improved forms nominated the 'averaged Reynolds' equation' and the 'flow factor' model were proposed by Charistensen et al. [13] and Patir et al. [14, 15] with a consideration of the specific roughness characteristics such as the shear flow factors, asperities crushes and the roughness directions. For the asperity contact mechanics, the conditions with or without bulk deformation during metal forming process were involved. Most investigations, however, were frequently conducted in terms of the bulk deformation case, including the important influence factors about the geometry, slope and amplitude of roughness, the flattening rate, the asperity hardness and the contact area. By contrast, the case of without bulk deformation was restricted to be used under the high strains [16].

The surface roughness of rolled specimens depends greatly on the work roll roughness, asperity flattening rate, roughness wavelength, real contact area, rolling speed, reduction rate, oil film thickness, and viscosity of lubricant [17-19]. Kijima et al. [20] explored the effects of work roll roughness on the strip elongation and roughness transfer of the rolled strip. In their study, the roughness of work roll was modelled with various pitch size. The results suggested that the bigger pitch with smaller roughness could result in a larger roughness transfer from work roll to rolled strip's surface. Moreover, rougher work roll was supposed to give a rise to a higher elongation due to the extended sticking region arose from the longer roll contact arc. Wu et al. [21] proposed a simplified method to analyse the roughness texture transfer during rolling process with a consideration of the influences of transient or non-steady rolling states. The results predicted that an increasing rolling reduction ratio could lead to a direct increase of the roughness transfer. In order to clarify the real contact area at the roll-workpiece interface in cold rolling process, Wilson et al. [22] developed an upper-bound model to study the asperity flattening behaviour. The modelling results showed highly consistency with that obtained by the experiments. Ma et al. [23] conducted a study aiming to understand the characteristics of the surface roughness transfer in cold rolling. After experimental work, they concluded that high rolling speed could benefit the symmetry of the surface condition, and lubrication could effectively help to reduce the sharpness of surface. An investigation on the spectrum of the surface roughness after foil rolling was carried out by Le et al. [24] by using the fast Fourier transform criterion to identify the variation features of different roughness wavelengths. Through this method, the position and geometry of the micro pits were clearly clarified and quantified. They also suggested that the longer wavelength elements were more easily subjected to be flattened than the shorter ones.

Although previous work has reported some surface roughness variation under different rolling and lubrication conditions during conventional rolling process, there is still few research on the alteration of surface roughness on the strips after micro flexible rolling. In this study, the mechanism of surface roughness alteration in relation to special deformation features of micro flexible rolling is clarified with considering the significance of various thickness zones, upward or downward rolling phases, rolling force, thickness ratio, rolling speed, roll lifting speed and lubrication condition.

2 Experimental

Micro flexible rolling was carried out on a two-high precision laboratory rolling mill, as shown in Fig. 1. The diameter of the work rolls was 25 mm, and the roll barrel length was 40 mm. The detailed rolling schedules without applying any front and back tensions were specified in Table 1. In the results and discussion part, rolling speed is denoted as RS, roll lifting speed is denoted as RLS, thickness ratio is denoted as TR and lubrication and dry conditions are denoted as L and D, respectively. The whole rolling processes were controlled by a self-designed PLC program. The rolling force was online measured by the high-precision force sensor. Then the information including the rolling force and online roll gap variation was obtained. The rolling speed was set in a range of 30-90 cm/min, and the rolling lifting speed was adopted between 200 and 400 μm/s. The thickness ratio was defined as the ratio of thickness at thicker zone to that of thinner zone, which differed in 1.43, 1.99 and 3.53, respectively. In addition, dry and lubrication interface conditions between work rolls and specimens were also considered.

In order to clarify the effects of various rolling parameters and tribological conditions on the surface roughness of micro flexibly rolled strips, various types of work rolls and specimen surface conditions were prepared, as shown in Fig. 2. For work rolls, two kinds of initial work roll surface roughness were taken. One of them was smoother cold work roll with a surface roughness of 0.46 μm. Another one was processed by grounding the rolls' surfaces to 0.81 μm using the 80 grit sandpaper along both the axis and rolling directions of work rolls. However, the final asperity direction mostly tends to the rolling direction since the last grounding step was finished parallel to this direction. 1060 aluminium strips with a thickness of 464 μm were cut into dimensions of 150 × 15 mm^2 for the current study. Surface roughness of 0.24 or 4.91 μm for the initial strips was applied. The rougher specimens were prepared with the sand blasting method to produce the isotopic and random asperities, as shown in Fig. 2(f).

VK-X100 3D laser scanning microscope was used to observe the surface morphology of the micro flexibly rolled strips. In addition, the arithmetical mean surface roughness (R_a) is the most frequently used parameter for surface roughness evaluation and thus it has been calculated and outputted for all cases. Measurements were conducted on each position for all kinds of thickness zones with three replicates under different rolling and lubrication conditions. Apart from the comparison of surface roughness alteration between the upward and downward rolling phases, other measurements were all finished in the downward rolling phase.

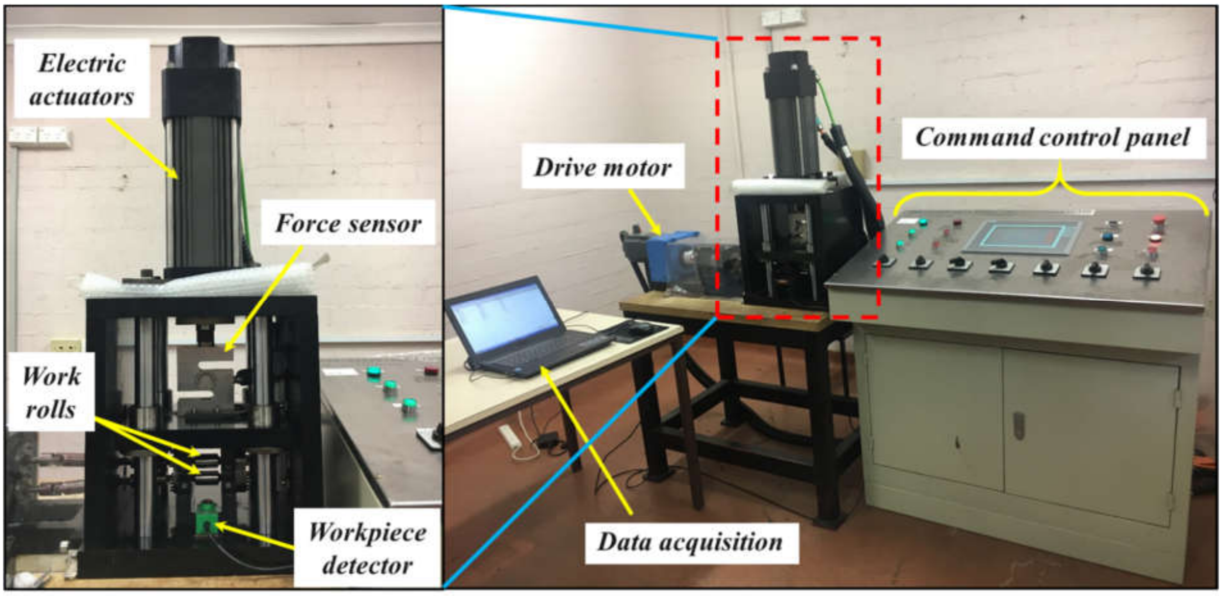

Fig. 1. Illustration of the micro flexible rolling system.

Table 1 Various rolling schedules of micro flexible rolling.

Specimen	R_a of work roll (μm)	R_a of specimen (μm)	Rolling speed (cm/min)	Roll lifting speed (μm/s)	Thickness ratio	Lubrication condition
S1	0.46	4.91	30	400	1.99	L
S2	0.46	4.91	60	400	1.99	L
S3	0.46	4.91	90	400	1.99	L
S4	0.46	4.91	60	300	1.99	L
S5	0.46	4.91	60	200	1.99	L
S6	0.46	4.91	60	400	1.43	L
S7	0.46	4.91	60	400	3.53	L
S8	0.46	4.91	60	400	1.99	D
S9	0.81	0.24	60	400	1.99	L

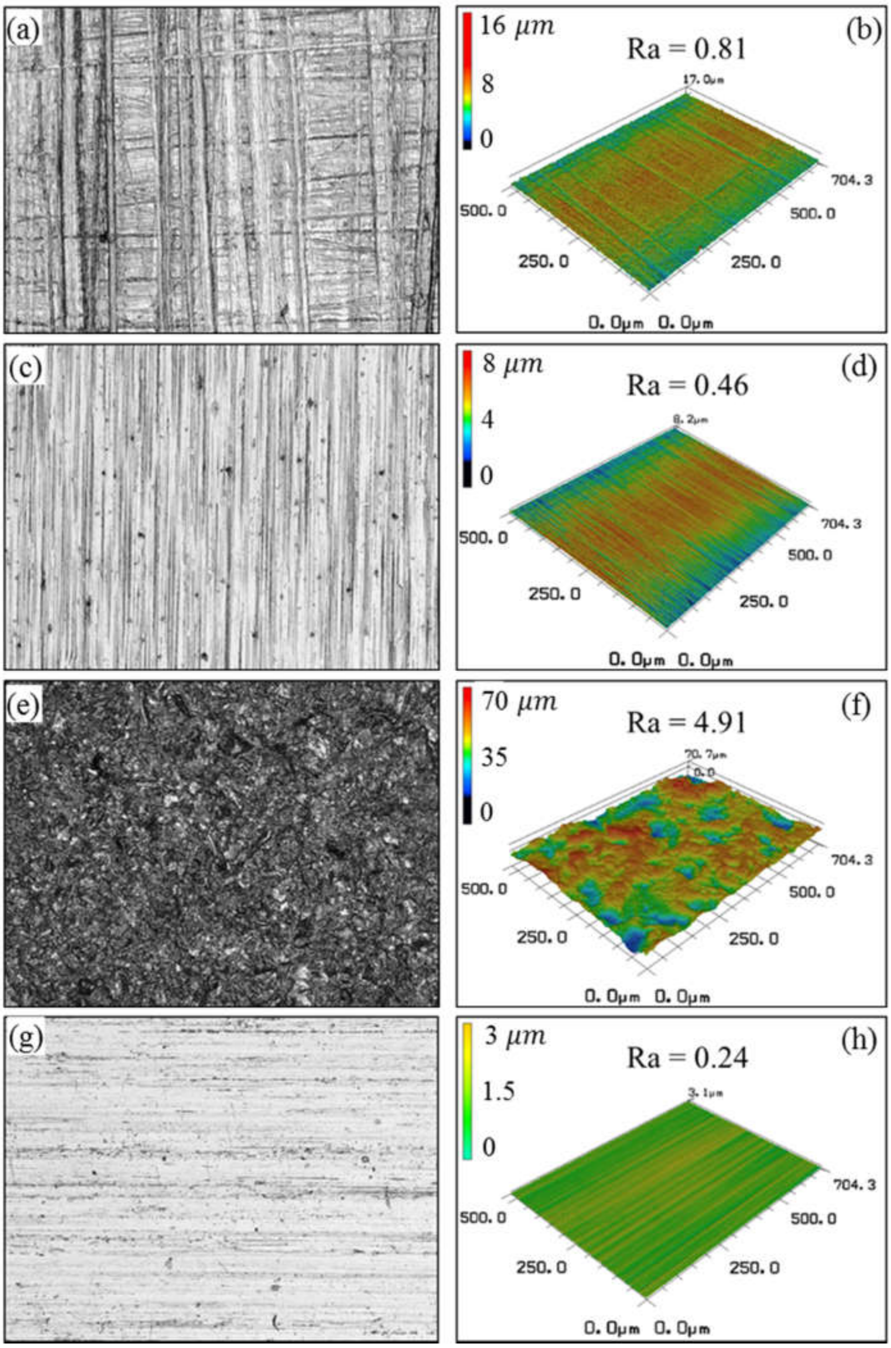

Fig. 2. Initial laser topography observation for the (a) rougher work roll, (c) smoother work roll, (e) rougher workpiece and (g) smoother workpiece, and 3D surface morphology for the (b) rougher work roll, (d) smoother work roll, (f) rougher workpiece, and (h) smoother workpiece.

3 Results and discussion

3.1 Surface roughness in different thickness zones

Fig. 3 shows the 3D surface morphology variation of MFRS in different thickness zones, which includes both the smoother roll case (S1) and the rougher roll case (S9). For the smoother roll case, the surface roughness alteration clearly indicates a big reduction from the thicker zone ($R_a = 2.94$ μm) to the thinner zone ($R_a = 0.60$ μm). Compared to the initial condition shown in Fig. 2(c), nearly a half fraction of flattening phenomenon occurs with some tightening troughs in the thicker zone (Fig. 3(c)). In the transition zone, most asperities are flattened to a smooth morphology. However, few non-homogeneous retention of isolated pockets or troughs are still observed in some areas, which is owing to the non-uniform local bulk deformation of surface asperities. Although there is a higher reduction performing on the thinner zone, the troughs remain accompanied by almost flattened surface condition with lower roughness height.

For the rougher roll case, the surface roughness is found to increase gradually from the thicker ($R_a = 0.46$ μm) to the thinner zone ($R_a = 0.62$ μm). The diverse variation tendency between the rougher and smoother roll cases means that the surface condition of work rolls takes up the dominant status in determining the alteration of workpiece's surface roughness. The 3D morphology in the thicker zone presents a slight imprint behaviour in both the longitudinal and transverse directions, which is supposed due to the corresponding smaller rolling reduction. With the progress of the downward rolling process, the longitudinal roughness dominates the 3D surface profiles since the longitudinal surface roughness of work roll is much robust.

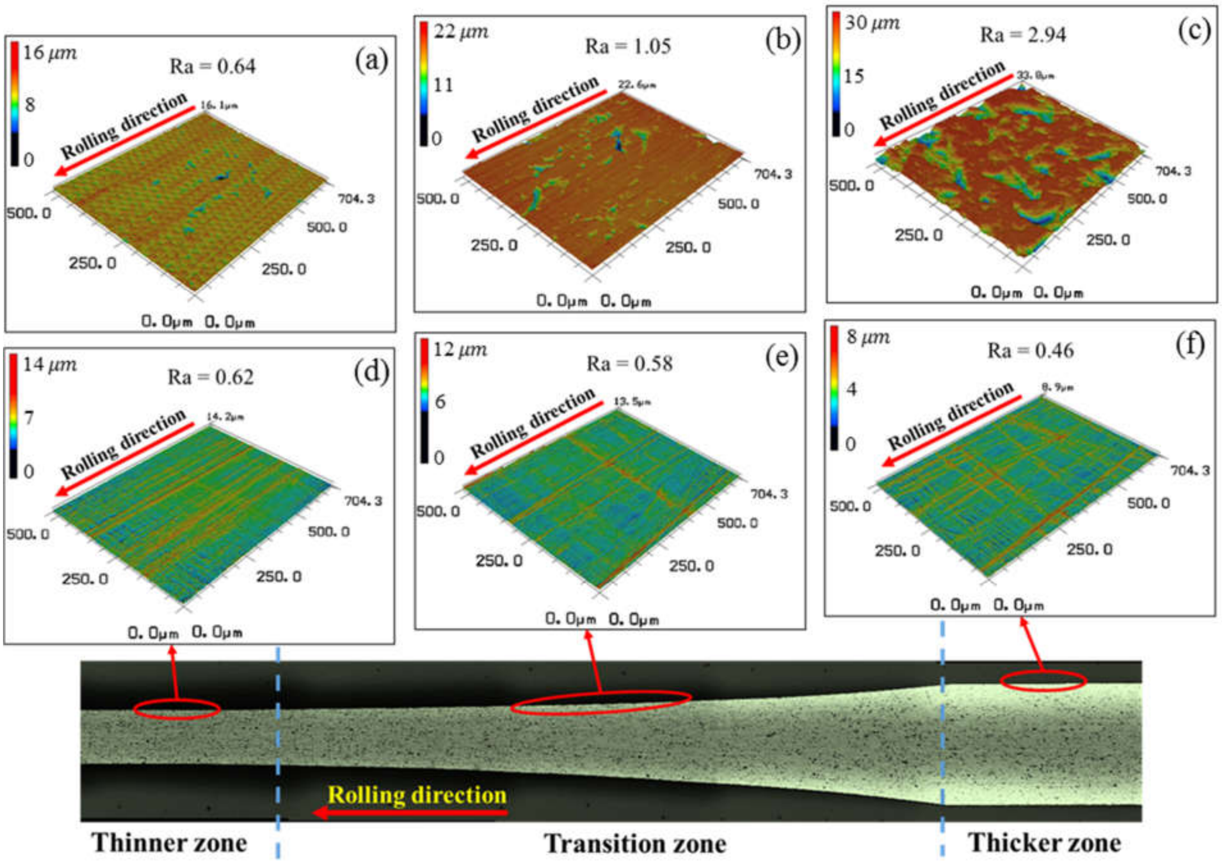

Fig. 3. Alteration of 3D surface morphology from the thick to thinner zones in downward rolling phase for the smoother roll case (a-c) and rougher roll case (d-f).

The laser topography of the rolled surface corresponding to the 3D surface morphology (Fig. 3) is shown in Figs. 4 (smoother roll case) and 5 (rougher roll case), in which the differences of surface roughness profiles between the longitudinal and transverse directions are presented. Similar to the results in Fig. 3, the surface roughness variation of the smoother roll case gradually weakens from the high the amplitude of vibration in the thicker zone to relatively low condition in the thinner zone. The peaks of their asperities have been flattened, which connect the remained troughs from the bulk deformation process. These troughs are frequently found on the isotropic surfaces produced by sand blasting. Sheu et al. [25] found that the geometry of these troughs could significantly affect the lubrication characteristics, in which the deeper troughs were supposed to carry the lubricant in the deformation zone. In addition, the crushed surface leads to a growing trend from the thicker to the thinner zones which accompanies with the increase of ploughing phenomenon. This is almost entirely conformed to the surface roughness obtained in Fig. 3. Obviously, it can be noted that there is a directional skewness of asperities happening in the thinner zone with a small height variation of about 6 μm, in which the slope of them tends to the opposite direction (marked with red arrows) from the rolling direction, as shown in Fig. 4(h). This is supposed that the big reduction performing on the thinner zone leads to a large surface elongation due to the specimen's high surface roughness layer, thus making a change of asperity direction and the extended sticking phenomenon [20]. These observations match well the results of 3D surface morphology in Fig. 3(a).

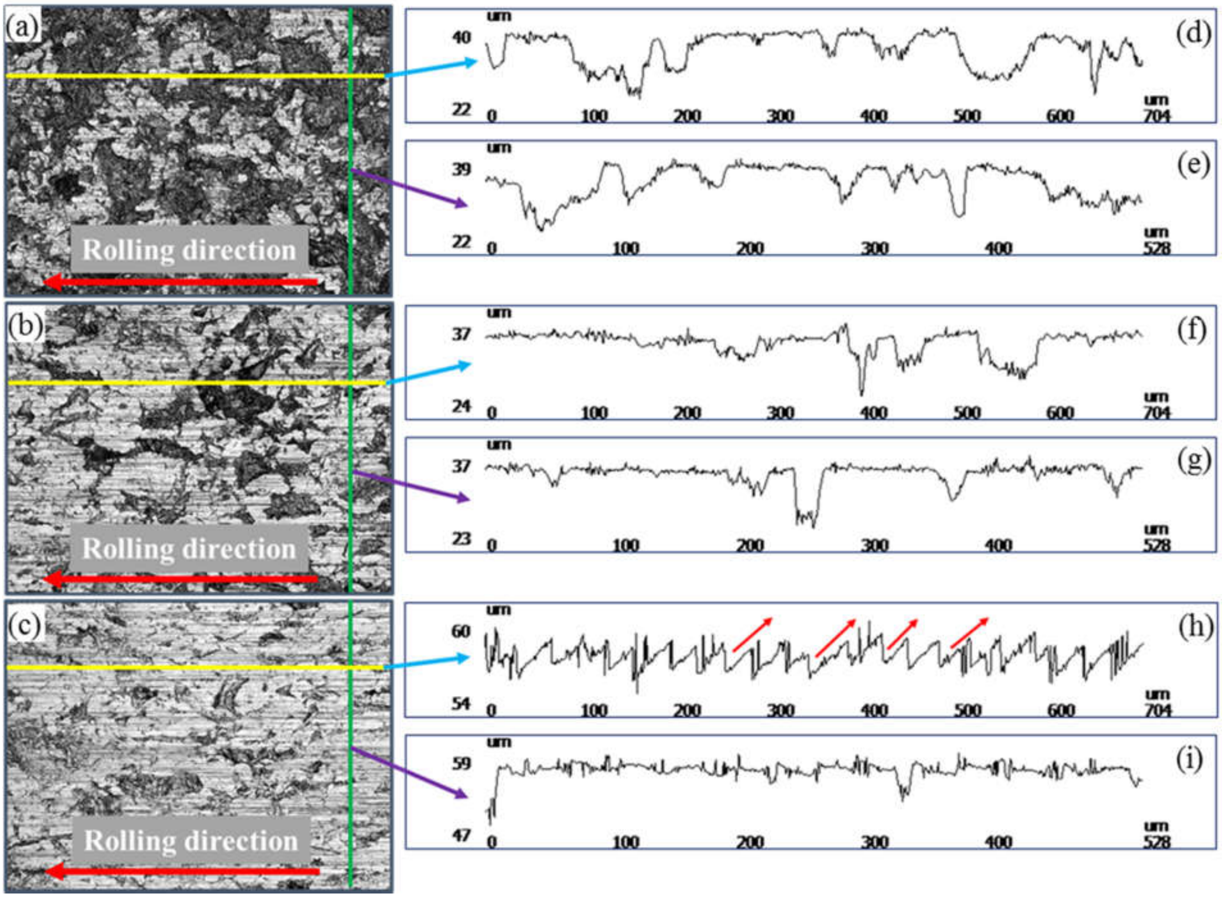

Fig. 4. Laser topography of the smoother roll case in the (a) thicker zone, (b) transition zone and (c) thinner zone, and the corresponding longitudinal roughness (d), (f) and (h), and transverse roughness profile (e), (g) and (i).

Fig. 5 displays the surface profiles variation from the thicker to the thinner zones for the rougher roll case, in which the thicker zone has the moderate amplitude and frequency of wave propagation. With the progress of downward rolling process, the surface becomes rougher and rougher from the thicker to thinner zone. It is worth to mention that the squama-like pieces emerge in both the thinner and transition zones. These normally happened in rolling with the rough work rolls which can extend the sticking zone and roll contact length [20]. Another reason can be understood that due to the rougher work roll original asperity along the longitudinal direction which is parallel to the rolling direction and cannot keep the lubrication very well. In this context, the slight roughness in the transverse direction will result in the flattening behaviour between the ploughed troughs from the longitudinal roughness of work rolls. Differently, asperities in the thinner zone display more vertical features rather than the tilting phenomenon occurred in the transition zone (marked with red arrows in Fig. 5(f)). This is supposed that is due to the simultaneous action of both linear roughness of work roll and the inherent characteristics of micro flexible rolling, in which the rolls reciprocate in the vertical direction which will separate the squama-like pieces into obvious teared layers with a certain tilting angle. Meanwhile, the features of this angle will undoubtedly have a close relationship with the resultant direction of the rolling speed and roll lifting speed performed on the transition zone.

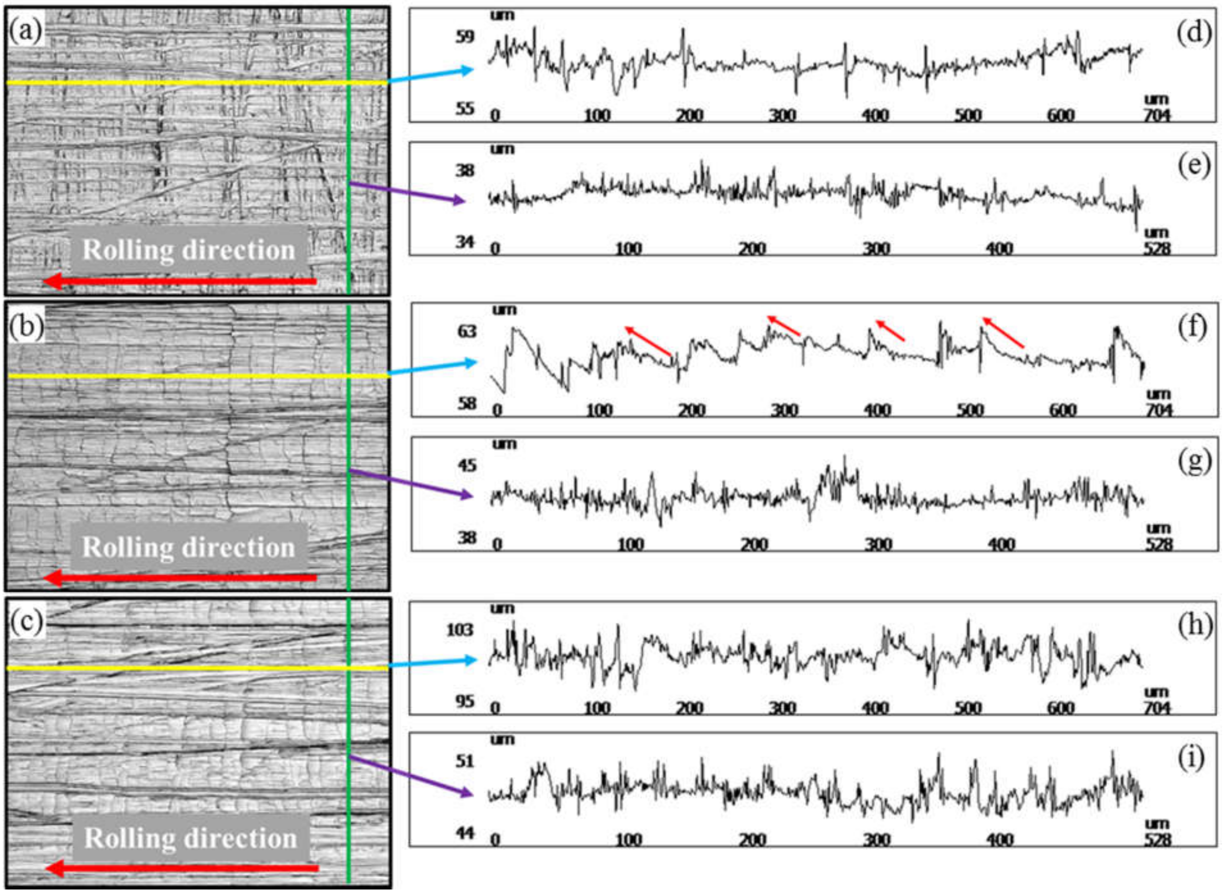

Fig. 5. Laser topography of the rougher roll case in the (a) thicker zone, (b) transition zone and (c) thinner zone, and the corresponding longitudinal roughness (d), (f) and (h), and transverse roughness profile (e), (g) and (i).

3.2 Effect of the rolling conditions

Fig. 6 shows the influence of various rolling speeds (30-90 cm/min) on surface roughness alteration, rolling force and MFRS profile in the thinner, transition and thicker zones, respectively. Evidently, the surface roughness has displayed an increasing trend with the increase of rolling speed in all thickness zones. It is obvious that a small variation is shown in the thicker zones since only a few rolling reduction performed on this thickness zone. However, it can be found that the higher rolling speed results in the occurrence of a bigger drop for the rolling force in all thickness zones. This is because that more volume of oil with the efficient entrainment will be trapped into the isolated pockets at the deformation zones with a climbing rolling speed [26]. In this case, the drawn oil can form a closed lubricant pocket which shares the load and prevents further crushing behaviour of asperities then leading to a decrease of friction coefficient during micro flexible rolling. In addition, Sheu et al. [27] found that a more notable increase of real contact area would take place at lower rolling speed. This is consistent to the hypothesis of Lenard et al. [28] that more boundary lubrication regime will be generated at lower rolling speeds, which also provides the evidence for the results obtained under various rolling speeds and the variation of rolling force.

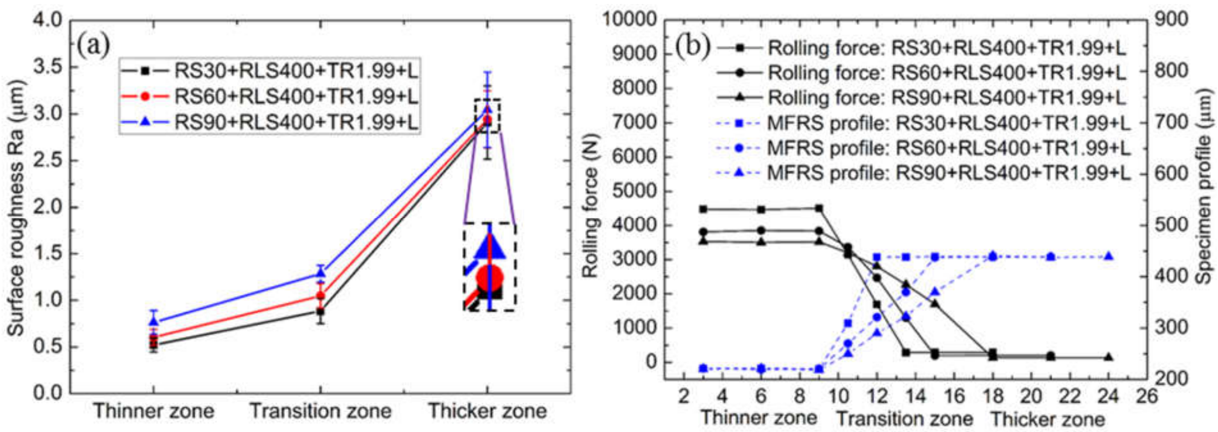

Fig. 6. (a) The surface roughness alteration, and (b) rolling force and specimen profile as a function of rolling speed in the thinner, transition and thicker zones, respectively.

Fig. 7 presents the results of surface roughness alteration, rolling force and MFRS profile with various roll lifting speeds (200-400 μm/s) in the thinner, transition and thicker zones, respectively. It can be found that there is not obvious effect of roll lifting speed on the variation of the roughness variation in both the thinner and thicker zones. By comparison, a slight difference can be observed in the transition zones, which drops from the specimen with the biggest roll lifting speed to the lowest roll lifting speed. It can be understood that a higher roll lifting speed will lead to a larger resultant surface speed along the transition zone, then the work roll can provide a larger momentum and kinetic energy to crush and/or flatten the asperities of the workpiece to a higher degree. In this case, the surface roughness with 400 μm/s rolling lifting speed has obtained the lowest surface roughness compared with the other two lower values. At the same time, the corresponding MFRS profile shows a lower roll lifting speed can induce a longer transition zone length since a longer duration is needed from the thicker to the thinner zones under this condition.

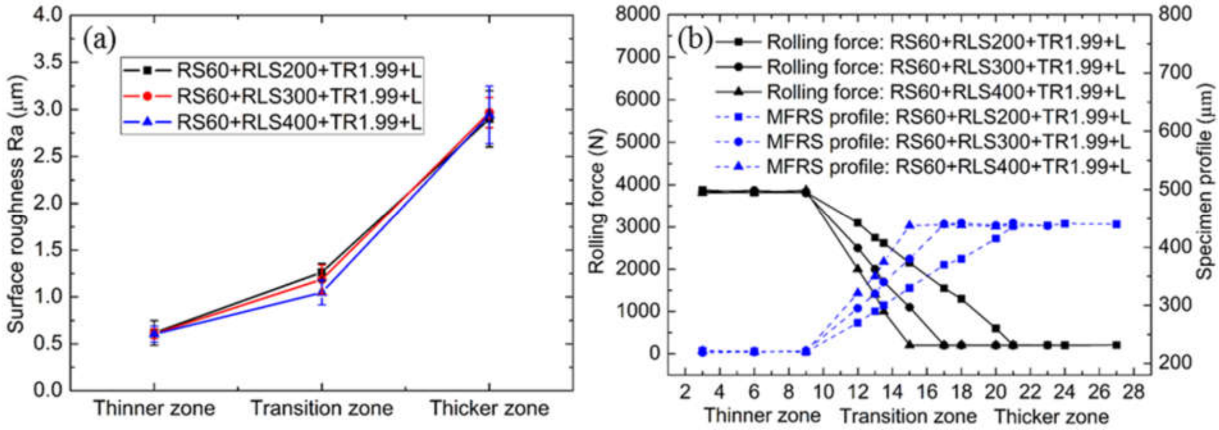

Fig. 7. (a) The surface roughness alteration, and (b) rolling force and specimen profile as a function of roll lifting speed in the thinner, transition and thicker zones, respectively.

Fig. 8 shows the roughness alteration, rolling force and MFRS profile with different thickness ratios in the thinner, transition and thicker zones, respectively. It can be found that the surface roughness gives a decreasing trend from the thicker to thinner zones, in which the progression of this trend becomes much more pronounced as the increase of thickness ratio from 1.43 to 3.53 in all thickness zones apart from the thicker zones with only slight change. It can be supposed that a higher reduction happened in the thinner zone can lead to a larger asperity flattening rate which driven by the pressure difference between the asperity and through and leads to a rapid growing rate of the real contact area [18, 27]. This emerges in conjunction with the results of the rolling force and MFRS profile. It should be noted that an extreme high rolling force is observed in the case of the highest thickness ratio of 3.53, which most likely attributes to the increase of strain hardening resulting from the accumulation of dislocations during the severe plastic deformation [29]. Becker [30] studied the influences of crystallographic properties, material homogeneity and strain localisation on the surface roughness alteration. They found that a higher strain hardening could lead to a lower surface roughening behaviour, which was supposed that a lower hardening disclosed more steady strain localisation then prompted a generation of stronger troughs at the earlier stage [30]. This demonstrates a highly agreement with the results obtained in the current study, in which higher thickness ratio presents a lower surface roughness.

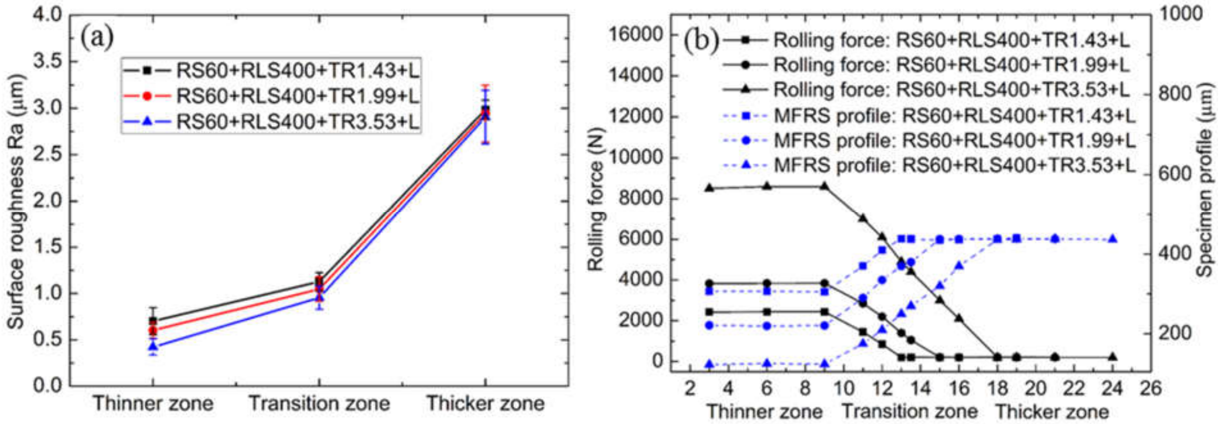

Fig. 8. (a) The surface roughness alteration, and (b) rolling force and specimen profile as a function of thickness ratio in the thinner, transition and thicker zones, respectively.

Fig. 9 shows the surface roughness comparison, rolling force and specimen profile of MFRS under dry and lubrication rolling conditions. The results shown in Fig. 9(b) present that the lubrication has a strong influence on the reduction of rolling force due to the mixed lubrication regime discussed in the introduction part. In addition, the more proportion of surface roughness layer lead to the less proportion of substrate layer, which can result in higher rolling force required from both roll edges kiss and work hardening from the plastic deformation. Regarding this, relatively big difference of rolling forces can be found between the dry and lubrication conditions. However, the variation of surface roughness is quite different from that of the rolling force in all thickness zones, in which relatively lower surface roughness can be obtained under the dry rolling condition. This can be understood that under the dry condition, the asperities of the surface are collapsed rapidly at the bulk deformation zone [31]. The directly metal-to-metal contact implies a great increase of both the friction coefficient and rolling force but inducing a great flattened rate of asperities. By contrast, rolling under the lubrication condition is supposed to be as a mixed lubrication regime, in which more trapped oil pockets are formed and make a contribution to share the deformation load. Accordingly, this can lead to a smaller volume of the flattened and crushed asperities hence a higher surface roughness. Fig. 10 has provided the visible evidence, in which a higher area of flattened asperities (brighter area) with certain ploughing phenomenon have been found from the results of the thicker zones in the case of dry rolling. With the progress of the downward rolling phase, the surface condition in the thinner zone has been almost flattened (Fig. 10(d)). By comparison, the surface condition under the lubrication rolling case still presents few troughs (darker area) which are supposed to hold the trapped oil pockets during bulk deformation then lead to a reduction of rolling force and a higher surface roughness.

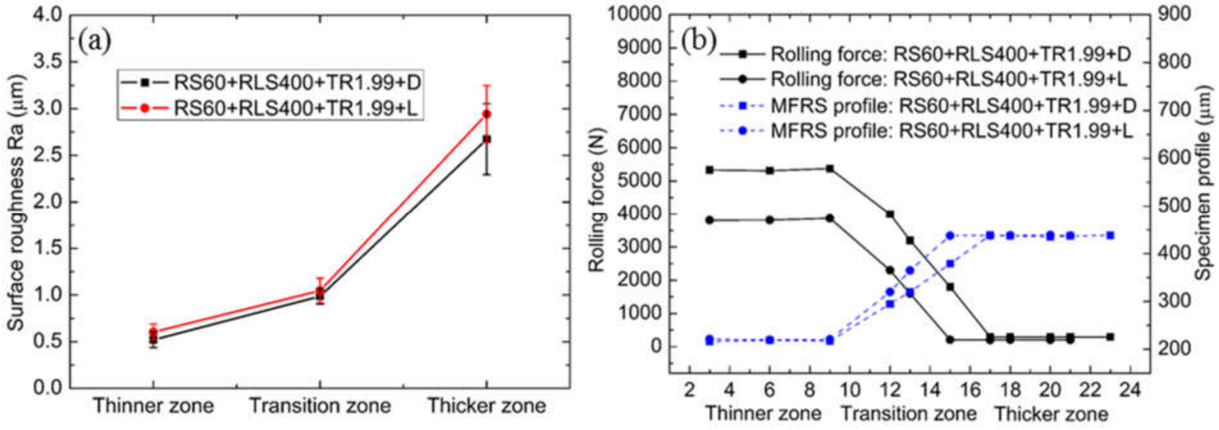

Fig. 9. (a) The surface roughness alteration, and (b) rolling force and specimen profile as a function of dry and lubrication conditions in the thinner, transition and thicker zones, respectively.

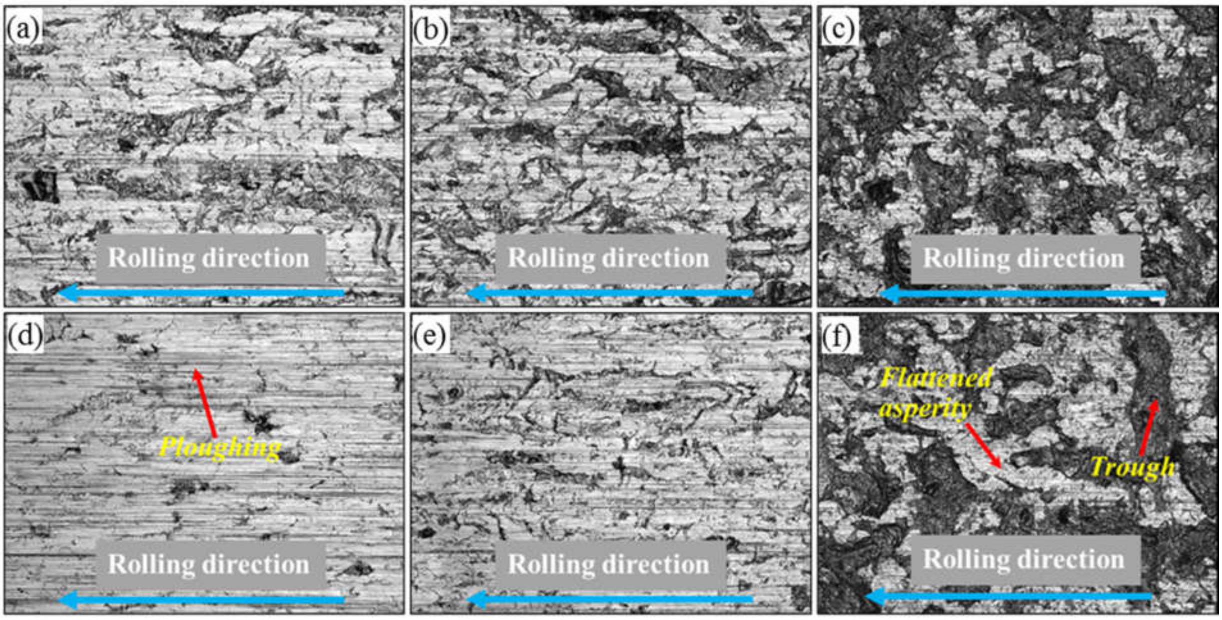

Fig. 10. Laser topography in the (a) thicker zone, (b) transition zone and (c) thinner zone under dry rolling condition, and the (d) thicker zone, (e) transition zone and (f) thinner zone under the lubrication rolling condition.

3.3 Surface roughness difference along the transverse direction

Fig. 11 shows the comparison of the surface roughness distribution along the transverse direction of the MFRS in the thinner, transition and thicker zones, respectively, in which both the smoother roll and rougher roll cases are involved. For the smoother roll case, it is clear that the surface roughness near the middle area obtains the relatively higher values comparing to that measured from the sides. Contrarily, relatively lower surface roughness were obtained for the rougher roll case. This is due to the potentially inevitable bending behaviour of the work rolls during rolling process, which can lead to the less contact in the middle between the work roll and workpiece along the transverse direction. The contact mechanisms are concluded and indicated in Figs. 12(a)-12(d), in which more asperities on the side are crushed for the smoother roll case while more deformed surface profile is slaved the work roll's surface morphology on the side of work roll-workpiece interface in terms of rougher roll case. Jiang et al. [32, 33] reported that this behaviour could significantly affect the precision of rolled products. Then they developed a model to optimise the rolling procedure and obtained a great improvement for the rolling process.

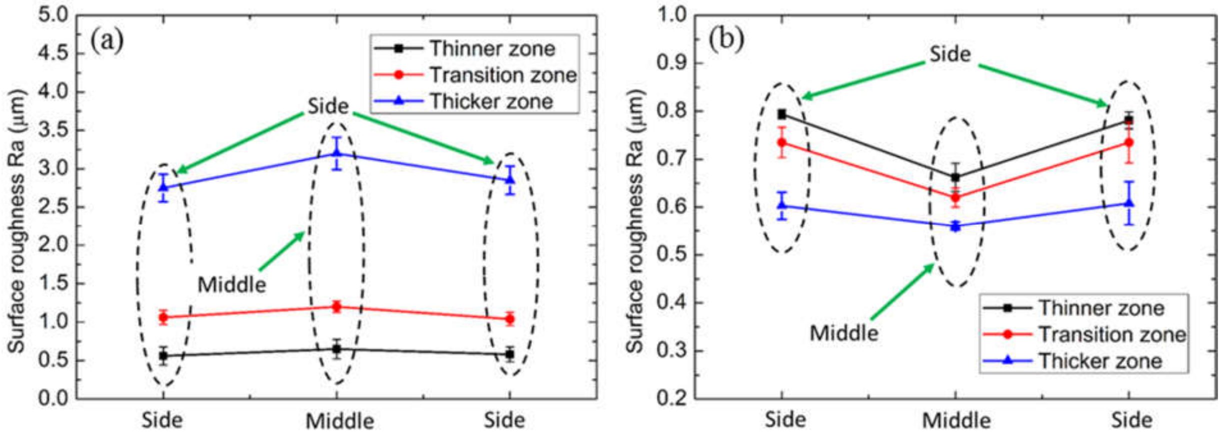

Fig. 11. Surface roughness variation in all thickness zones of MFRS for the (a) smoother roll case, and (b) rougher roll case.

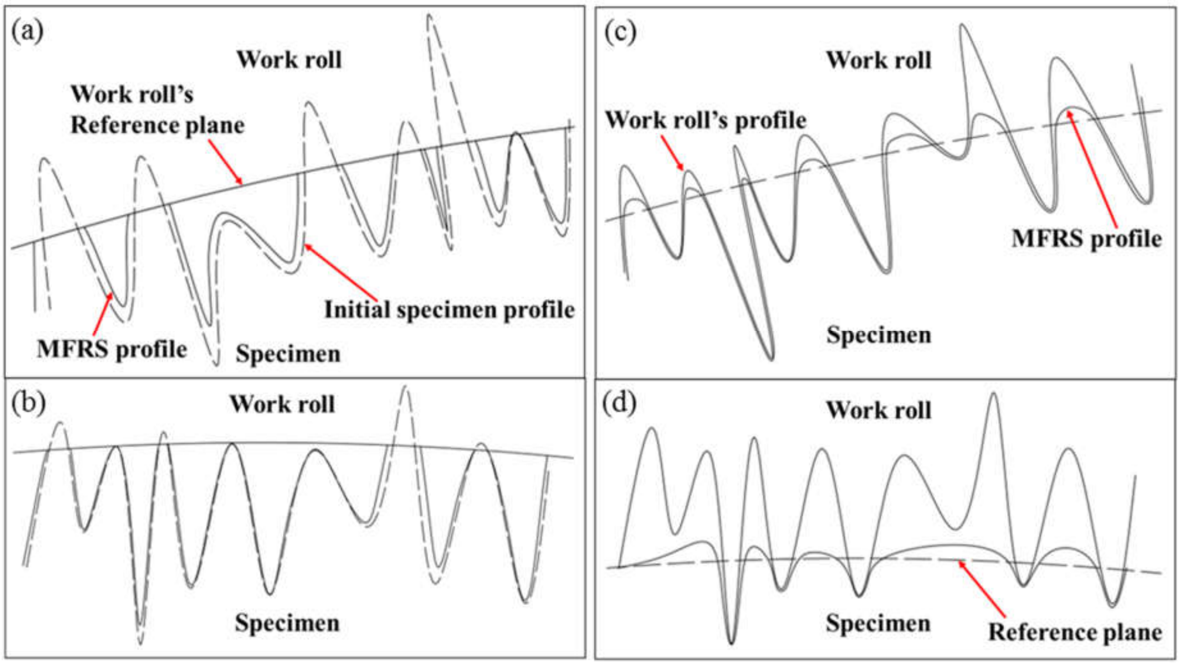

Fig. 12. Graphic diagrams on the (a) side and (b) middle of MFRS for the smoother roll case, and (c) side and (d) middle of MFRS for the rougher roll case.

3.4 Surface roughness alteration during upward and downward rolling phases

Fig. 13 shows the comparison of the surface roughness alteration, rolling force and MFRS profile in different thickness zones during upward and downward rolling phases. It can be found that the surface roughness in the transition zone under the downward rolling phase displays a slight higher value than that in the upward rolling phase. Meanwhile, MFRS in the downward rolling phase also presents a continuously larger rolling force. The mechanics to explain the comparison results between the upward and downward rolling phases has been shown in Fig. 14. Owing to the special rolling feature of the downward rolling phase, it is supposed that the oil pool will be formed at the outlet region of roll bite, as shown in Fig. 14(b). This oil pool may transfer the rolling regime from the mixed one to the hydrodynamic one. To the well-known Stribeck curve, it is expected that during the hydrodynamic lubrication regime (downward rolling phase) the friction coefficient will present a high value comparing with the mixed lubrication regime (upward rolling phase) [34]. In this context, micro flexible rolling under the downward rolling phase with the same online adjustment thickness will present a larger value in both rolling force and surface roughness comparing to the upward rolling phase. In addition, the downward rolling phase can possess a bigger roll bite angle and a longer roll contact arc, which is also a non-ignorable factor resulting the higher rolling force in the downward rolling phase. These results are highly consistent with the experimental results obtained by Liu et al. [35, 36].

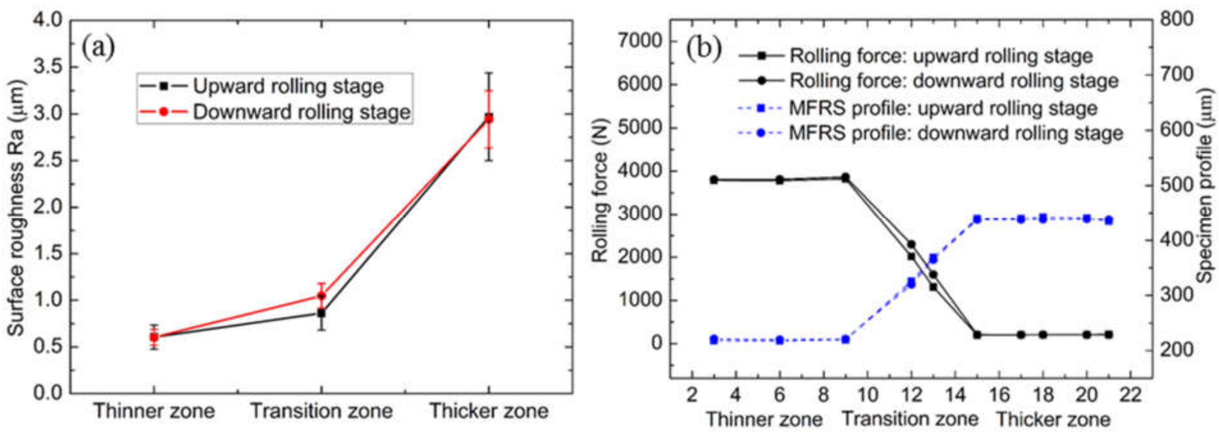

Fig. 13. (a) The surface roughness alteration, and (b) rolling force and specimen profile as a function of upward and downward rolling phases in the thinner, transition and thicker zones, respectively.

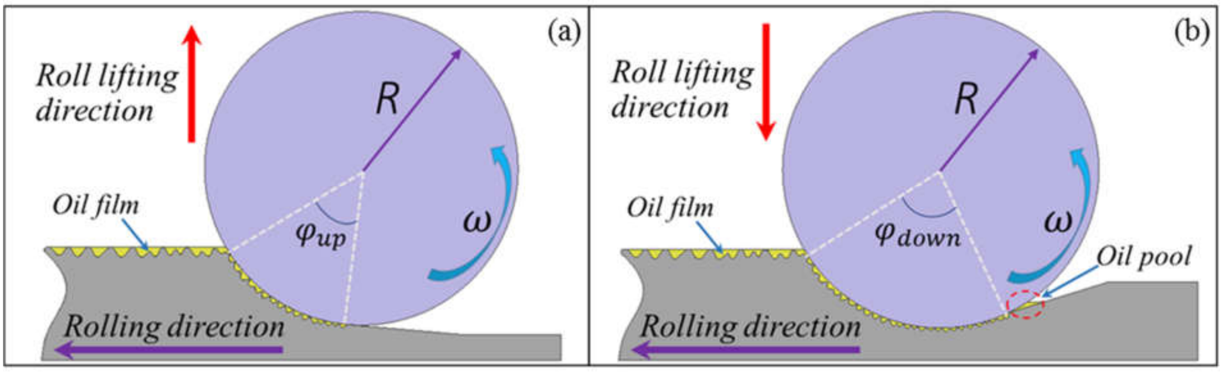

Fig. 14. Micro flexible rolling with the (a) upward rolling phase, and (b) downward rolling phase.

4 Conclusions

1. A decreasing tendency of surface roughness alteration of MFRS from the thicker to thinner zone for the downward rolling phase is observed for the smoother roll case. By contrast, the rougher roll case presents an entirely opposite alteration trend of surface roughness from the thicker zone to thinner zone.
2. Directional skewness of the rolled asperities on the surface of MFRS has emerged in the thinner zones for the smoother roll case but in the transition zone for the rougher roll case.
3. A growing thickness ratio can gradually result in a falling surface roughness from the thicker to thinner zones. An extremely high rolling force is obtained in the thinner zone with the highest thickness ratio, which is supposed to the emergence work hardening behaviour.
4. Compared to the dry rolling condition, MFRS after lubrication rolling condition presents a big reduction in rolling force but a certain increase of surface roughness.
5. Surface roughness near the middle area in the transverse direction has a higher value for the smoother roll case but a lower value for the rougher roll case.
6. Compared to the upward rolling phase, MFRS in the downward rolling phase gives a rise to the occurrence of oil pool at the outlet of roll bite area, which will modify the lubrication regime from mixed lubrication regime to the hydrodynamic lubrication regime, and then cause an increase both the surface roughness and rolling force in the transition zone. In addition, the bigger roll arc length also contributes to the high rolling force in the downward rolling phase.

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